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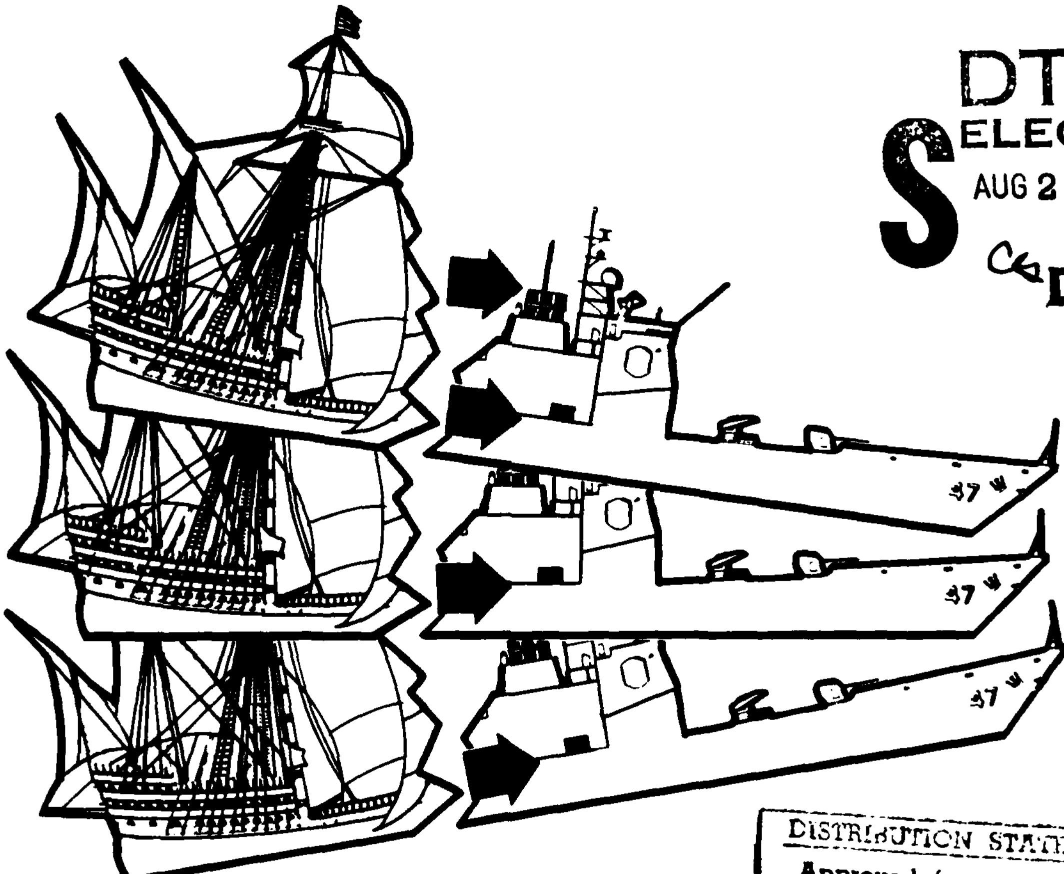

NEW TECHNOLOGY IN OIL CONTENT MONITORS

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Notations, Definitions and Abbreviations

APD	- Avalanche Photo Diode
GRIN	- Graded Index
NAVSEA	- Naval Sea Systems Command
OCM	- Oil Content Monitor
OWS	- Oil Water Separator
OWPS	- Oily Waste Processing System
PIN	- Positive Intrinsic Negative
PPM	- Parts per Million
UV	- Ultraviolet

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ABSTRACT

International anti-pollution requirements have been legislated to regulate the oil content of bilge effluent from ships. In response to these standards, the U.S. Navy is currently in the process of installing pollution abatement equipment on all vessels. The equipment will consist of an oil/water separator in the bilge discharge line, followed by an oil content monitor which makes the final decision on whether or not the water is clean enough to be pumped overboard. The monitor is required to make a real time measurement of oil concentration in the range 15 $\pm$ 5 to 100 $\pm$20 ppm for flow rates up to 50 gal/min. and possibly in the presence of interfering contaminants, such as rust.

This paper presents the results of the current effort to develop a monitor which satisfies all of these requirements and is sufficiently rugged for fleet deployment. The monitor under development employs two fiber optic systems and a small microprocessor. The first optical system measures the concentration of particles in the flow as a function of their sizes, using small angle forward scattering. The second determines what percentage of the particles in the flow are oil, using large angle scattering. The microprocessor takes the data from the two optical systems and calculates the oil concentration in the flow. Since the particle size is measured by the monitor, no sample preparation is required and the monitor may be placed directly in the discharge line where it responds to changes in oil content in less than one second. In addition, this monitor can notify the operator of impending oil/water separator failure associated with passing large oil particles.

A demonstration monitor consisting of the forward scattering unit has been successfully tested at the NAVSEA oil pollution abatement test facility at the Philadelphia Naval yard. The monitor agrees well with chemical means of measuring oil content. Results of this comparison and laboratory tests of a prototype instrument that features contaminant discrimination will be presented.

I. INTRODUCTION

The Navy is committed to limiting environmental damage resulting from the discharge of bilge and ballast effluent. Limits on the oil content of waste water that may be pumped overboard have been enacted on all levels from local regulations to international agreements. Specific naval directives concerning oil content of shipboard effluent are presented in Appendix A. To achieve compliance with the Navy directives, the NAVSEA Oil Pollution Abatement Program is retrofitting Navy ships with Oil Water Separators (OWS) and Oil Content Monitors (OCM). The OWS will reduce oil concentrations in the discharge and the OCM will insure that the Oily Waste Processing System (OWPS) meets performance requirements.

The Oily Waste Processing System is shown in Figure 1. The hardware includes transfer pumps for bilge effluent and oily waste, storage tanks for waste oil and oily waste, as well as the Oil Water Separator and the Oil Content Monitor. Oily bilge effluent or ballast water is passed through the OWS, where oil is separated and transferred to the waste oil holding tank. The oil concentration in the effluent water is then evaluated by the Oil Content Monitor. If the oil concentration exceeds the permissible level, the effluent is routed either to a holding tank or back into the bilges for further processing. The proper function of the Oily Waste Processing System is determined and reported by the Oil Content Monitor.

The current discharge limits set by Federal regulation are 15 ppm of oil in the effluent while within 12 nautical miles of shore, and 100 ppm of oil while under way at sea. There have been no limits established for other insoluble contaminants, such as dirt, rust, algae and organic material; however, the Oil Content Monitor must be able to operate properly with these interfering particulates in the stream. In addition to the sensitivity and accuracy requirements, the OCM must be able to function in the shipboard environments with no adverse effects from vibration, electromagnetic interference, or other ship systems. The monitor must not interfere with the normal operation of the ship through EMI, or unsafe operation.

II. REVIEW OF CURRENT TECHNOLOGY

A wide variety of OCM concepts and technologies have been evaluated (Bird '74), and the most useful methods are summarized in Table 1, along with their major limitations. Current OCM concepts include chemical, physical and optical methods of determining oil content. Chemical extraction methods are not suitable for in-line use to provide real-time response, since the standard method of determining oil concentration involves a laboratory chemical analysis. The physical concepts include techniques such as acoustical propagation and electrical conductivity. These methods are extremely sensitive to air bubbles, and are not sensitive enough to cover the oil content range required for the OCM application. Optical concepts are currently the most promising methods for use in Navy oil content monitors.

<< Bruce L. Bird. Naval Ship Research and Development Center, "Oil-in-Water Monitors: A Review of the State-of-the Art." Report #4429, November, 1974.>>

Table 1. Current Methods for Determining Oil Concentration in Bilge Water.

METHOD	MAJOR LIMITATION
UV ABSORPTION	NOT SPECIFIC TO OIL
IR ABSORPTION	NOT SPECIFIC TO OIL
FLUORESCENCE	DEPENDENT ON DROPLET SIZE
ELECTRICAL CONDUCTIVITY	HIGH CONCENTRATIONS ONLY
ACOUSTICAL PROPAGATION	HIGH CONCENTRATIONS ONLY
CONVENTIONAL LIGHT SCATTERING	NOT SPECIFIC TO OIL DEPENDENT ON DROPLET SIZE

The optical methods include ultraviolet and infrared absorption, fluorescence and light scattering. Optical absorption measurements are made by passing a beam of light through a sample and determining the attenuation which is related to the concentration of oil in the beam. The absorption of UV light is a property of many organic molecules, and thus dissolved organics such as surfactants may interfere. In addition, the UV absorption efficiency will vary for different types of oils. Absorption of infrared light arises from certain chemical functional groups in the oil molecules. As with UV absorption methods, the presense of dissolved organics and variations of absorption efficiencies will reduce the accuracy of infrared absorption measurements.

Fluorescence is the sequential absorption and re-emission of optical radiation. A beam of light is passed through a sample and the fluorescence signal is observed normal to the input beam. Fluorescence is more specific than absorption since it probes two specific energy levels of the molecule, but variations in fluorescence efficiency between oils do occur. One problem specific to fluorescence methods is the reabsorption of the emitted radiation. This is a function of the size and concentration of oil droplets and leads to uncertainties in the concentration measurement of the droplets if the droplet size distribution is not well defined. In absorption and fluorescence methods, attenuation arising from the particles scattering the optical beams cannot easily be separated from the measurement. Therefore, parameters such as size and refractive index of the oil droplets will affect the concentration measurement.

Traditionally, light scattering techniques have involved the measurement of the optical power lost as the beam is transmitted through a sample (turbidity) or the scattered intensity at a single angle (nephelometry). The scattering of light in general is dependent upon the oil droplet size and refractive index as well as the concentration of droplets. Current light scattering methods, based on only one or two measurements, contain assumptions as to the droplet size distribution. Only a small fraction of the available information is actually being used in these methods.

In order to overcome the limitations of these optical methods, current commercial systems generally use a sample preparation scheme to reduce the effects of varying oil droplet size. These systems first attempt to take a representative sample of the flow. Next, some emulsification process is used to reduce the particle size to a reproducible distribution. Finally, the optical method is used to measure the oil concentration. These monitors do not operate in real time, since it can take up to 15 seconds to prepare and evaluate the sample. In addition, special installation may be required.

There are common technical problems faced by all optical methods of oil content monitoring. Fouling of the optical surfaces will degrade system performance. Other non-oil contaminants may be present, and different types of oil will be encountered. In addition, the harsh shipboard environment and available maintenance and operating personnel must be considered. A detailed technical review of the challenges found in the development of an oil content monitor is contained in a study by the British group at Standard Telecommunications Laboratories (Snel, '83).

<<Snel, D. and P.H., G.D. 'Oil Content Monitoring (Practical Considerations)", International Conference on Optical Techniques in Process Control, Paper A3 (1983).>>

III. FIBER OPTIC OIL CONTENT MONITOR

Since available commercial monitors have proved inadequate for the full extent of OCM application, NAVSEA is exploring the use of recently developed laser, fiber optic and microprocessor technologies. These technologies have been successfully developed and tested and have significant potential for future Navy shipboard OCM and other fluid system applications.

An in-line fiber optic oil content monitor is being developed under NAVSEA contract based on light scattering techniques combined with a microprocessor based data reduction scheme to increase the amount of information derived from the light scattering techniques. For this discussion, it is convenient to view light scattering as a combination of the two processes shown in Figure 2. A more rigorous description of light scattering theory is presented in Appendix B.

The first process, refraction, occurs when light passes through an interface between two different transparent materials. The path of the light is bent in the same way light is focussed with a lens--possibly through angles as large as 180°. A second process, diffraction, occurs when the particle size is of the order of the wavelength of light (a few microns). In this case the light path is bent without passing through the particle. Light scattered in the near forward direction is dominated by the diffraction process. Since diffration occurs outside the particle, only the particle sizes and concentrations are important, not the particle type. The Fiber Optic OCM measures the forward scattered light to determine the total contaminant concentration and particle size distribution. To determine what fraction of the total contamination is oil, measurements are made of the light refracted to large angles. These data are used to correct the measurement to yield only the oil content.

The OCM developed under Navy contract promises several major improvements over the current state of the art. It determines the oil content of the effluent stream in real time without processing the sample. The response bandwidth has been chosen to limit noise in the photodetector circuits, and to sample a representative part of the stream in a period of less than one-half second. The real time response will insure that no spills occur while the monitor is making a measurement, which is of interest for compensated ballast systems. Fiber optics are particularly well suited to the naval environment since they do not corrode, are EMI resistant and relatively lightweight and, once installed, are very rugged. This fiber optic oil content monitor is generally applicable to many multiphase flow systems such as fuel distribution networks.

Experimental Apparatus

The in-line fiber optic oil content monitor consists of two optical systems. The forward scatter system is shown schematically in Figure 3. An inexpensive solid state laser is used as the source. It generates 5 milliwatts of light at 780 nm. A 100-micron-diameter optical fiber is attached to the laster diode and transmits the light to the in-line scattering cell. The optical fiber acts as a point source at the focal point of a collimating lens. The collimated beam passes through an optical window into the flow stream. Scattered and unscattered radiation pass through another window to a collecting lens and forward scattered light is focused onto a linear array of fiber optics located in the focal plane of the collecting lens. Each detector fiber has a 400-micron-diameter core. Radiation is transferred from each detector position to individual PIN diode photodetectors. The signals from the detectors are then digitized and transferred to a microprocessor system for analysis.

The diffraction pattern observed in the forward direction will vary for different particle sizes according to Fraunhofer diffraction theory, which is presented in Appendix B. To calibrate the monitor, scattering patterns are determined for a range of different standard particles. Then an n by m matrix is created by collecting the response per unit concentration of n detectors for m different particle sizes. This calibration matrix is then inverted to give the transformation matrix, which relates the detector responses to the concentration of each particle size.

Once the particle size distribution and total contaminant concentration have been determined, the large-angle scatter system can be used to discriminate between oil droplets and other contaminants. The large-angle scatter system shown in Figure 4 uses a high-power pulsed laser diode. This light source provides 904 nm radiation in 50 nanosecond pulses with a peak power of 10 watts and a 1 KHz repetition rate. Light is transmitted from the laser through a fiber to a gradient index (GRIN) lens assembly which consists of a GRIN lens attached to the end of the fiber with optical adhesive. The lens and fiber are mounted inside a fine-bore stainless steel tube. This 1/8-inch-diameter stainless steel tube is mounted in a Swagelock fitting. A collimated beam passes into the flow system from this lens assembly, and identical lens assemblies are used to collect the radiation scattered at various angles. Collected radiation is transmitted through optical fibers to avalanche photodiodes with high-speed detector circuits. Peak detectors are used to hold the signals for the analog-to-digital converter.

Since large angle scattering is primarily the result of refraction of light passing through the particle, the particle composition determines the intensity distribution of the refracted light. When the contaminant concentration determined from the forward scatter data exceeds the permissible level, the large angle scatter data is used to correct the response and reject contaminants other than oil.

Results of NAVSEA Tests

Tests on the forward scatter system were conducted at the Naval Sea System Engineering Station's oil/water separator test facility at the Philadelphia Naval Shipyard. The flow system operates at 50 GPM through a 2-inch-diameter pipe. The separator was not operated, simulating separator failure. Oil was injected upstream from the contamination monitor. The results of a run are presented in Table 2, where chemical analyses were performed according to ASTM D-3921. The monitor response, obtained by matrix inversion as described above, is in excellent agreement with the injection rate and chemical analysis data.

Table 2. Comparison of Chemical Analysis and Oil Content Monitor Determination of Concentration in PPM.

MEASURED INJECTION RATE	CHEMICAL ANALYSIS	MONITOR RESPONSE
0.0	0.5	0.0
12.5	10.2	12.0
25.9	23.3	19.0
76.8	61.4	59.0
100.8	82.3	80.0
0.0	0.8	0.0
0.0	0.5	0.0
12.0	12.2	10.0
26.9	24.6	19.0
76.8	66.8	70.0
96.0	80.3	88.0
0.0	0.5	0.6

Table 3. Linear Regression of Oil Content Monitor Response and Chemical Analysis versus Injection Rate.

	E	C_{offset}	R
OCM	.85	-.8	.985
Chemical Analysis	.82	1.3	.998

The data is shown graphically in Figure 5 with the bars representing the limits of 15 ± 5 and 100 ± 20 ppm.

A linear regression of each data set is presented in Table 3. The data was fit to the equation:

$$C_{measured} = E\, C_{actual} + C_{offset}$$

Where E is the monitor efficiency and C_{offset} is the measured concentration with no contaminants present. The linear regression coefficent R is also presented in Table 3.

IV. DEVELOPMENT SCHEDULE

The development of the in-line fiber optic oil content monitor is a three-phase effort. Phase I involved the investigation of fiber optic techniques for oil-in-water monitors. Two concepts were investigated: The first was based on the refractive index dependence of light lost from the sides of an optical fiber. A bare fiber would be exposed to the contaminated flow. As the oil concentration increases, more light escapes from the fiber. This concept proved unreliable, since the surface of the fiber could be poisoned over long periods of operation. The second concept investigated was the fiber optic light scattering technique. A survey of the available fiber optic, laser and microprocessor technology and light scattering theory indicated that a new generation of oil content monitors could be developed.

The Phase II effort was directed toward the development of a prototype system to demonstrate the new technologies. In this phase, laboratory tests of the oil content monitor subsystem were conducted. Data were taken with a large-angle scatter system for different-sized test particles as well as samples of bilge effluent. A separate system was constructed to demonstrate the forward scatter technique with fiber optics and real-time microprocessor-based data reduction.

In the current Phase III, the large-angle scatter system for the discrimination against interfering particulates will be tested. The oil content monitor will then be designed to shipboard requirements for shock and vibration, reliability and maintainability MIL standards. This will require hardening of the optical system, choosing one of the available methods for maintaining the integrity of the optical surfaces, and reducing the electronics to a small, reliable package with easily understood controls.

V. CONCLUSION

The complexity of bilge effluent limits the usefulness of available commercial oil content monitors. Variables such as the type of oil, the oil droplet size and the presence of other contaminants lead to erroneous oil concentration measurements with these systems. While the basic concepts of the commercial systems cannot overcome these problems, an improved light scattering system has been designed which will effectively measure each of the variables and yield an accurate oil content.

The feasibility of the improved light scattering contamination monitor which addresses the shortcomings of the current systems has been demonstrated. The limitations of simple light scattering techniques have been overcome through data analysis with microprocessor technology while laser diodes and optical fiber technology make the system compatible with the harsh naval environment. The successful completion of the current phase of the development effort will yield an optical monitor ready for widespread naval use.

APPENDIX A

LEGISLATION AND REGULATIONS APPLICABLE TO THE NAVY OIL POLLUTION PREVENTION PROGRAM

Federal Legislation

a. Executive Order 12088 requires federal agencies to comply with the same pollution control standards that are applicable to the private sector. This includes all substantive, procedural, and other requirements. Exemptions may be granted by the President if "(a) in the interest of national security, or (b) in the paramount interest of the United States."

b. The Clean Water Act prohibits the dischare of oil in harmful quantities into navigable waters or into the 3-mile territorial waters of the United States. Quantities considered harmful are those that violate applicable water quality standards, cause a sheen or discoloration of the water surface, or cause a sludge or emulsion to be deposited beneath the surface of the water. This prohibition extends to federal facilities, including naval vessels.

c. The Act to Prevent Pollution From Ships implements the 1978 Protocol to the International Convention for the Prevention of Pollution From Ships (MARPOL). The Act became effective on 1 October 1983 and implemented the Protocol's standards for the design, construction, and operation of new and existing vessels. It specifically limits the oil content of ship discharges to less than 15 parts per million (ppm) within 12 nmi from shore, and to less than 100 ppm beyond 12 nmi. This in effect prohibits the direct discharge of oily bilge water at sea without prior processing through an effective oil water separator. DoD ships are exempted by the law, but DoD is required to prescribe standards consistent with the Protocol, without impairing the operations or operational capabilities of the ships.

DoD Environmental Regulations

a. DoD Directive 5100.50, "Protection and Enhancement of Environmental Quality," dated 24 May 1973, requires all DoD components to "take such measures as necessary to ensure compliance with applicable environmental quality standards and environmental performance specifications."

b. DoD Directive 5100.50, "Prevention of Oil Pollution From Ships Owned or Operated by the Department of Defense," dated 14 June 1985, implements the Act to Prevent Pollution From Ships by prescribing operational standards and equipment requirements for DoD ships consistent with those of the international MARPOL Protocol. The oil content of ship discharges is limited to less than 20 ppm within 12 nmi from nearest land to less than 100 ppm beyond 12 nmi.

Navy Environmental Regulations

a. SECNAV Instruction 6240.6D, "Responsibilities for Department of the Navy Environmental Protection Program," dated 31 January 1975, requires the Navy to act in accordance with appropriate environmental legislation, Executive Orders, and regulatory standards. Naval ships in foreign harbors are to conform to pollution control standards set forth in applicable international, bilateral, status of forces, and port clearance agreements.

b. OPNAV Instruction 5090.1, "Environmental and Natural Resources Protection Manual," dated 26 May 1983, prescribes Navy policy and assigns responsibilities for protection and enhancement of the environment. The Instruction prohibits Navy ships from discharging oil and oily wastes into waters within 50 nmi of the nearest shoreline. The new draft contains a stipulation that requires shipboard installation of Oil Water Separators, Oil Content Monitors, and other oily waste processing equipment. Additional revisions are currently being developed to reflect the requirements and operational standards of the recently promulgated DoD Directive 6050.15. These latest revisions will allow ships within 12 nmi from neearest land to discharge oily wastes of less than 20 ppm, and beyond 12 nmi of less than 100 ppm.

c. NAVSEA Instruction 5090.1 (formerly 6240.1A), "Shipboard Environmental Quality Program," specifies that maximum effort be directed at incorporation of environmental pollution protection features in the basic designs for ships and shipboard systems/equipments. The Instruction is currently being revised to better delineate shipboard environmental protection responsibilities of the various command directorates. Promulgation is expected during FY 1986.

d. Article 1121 of U.S. Navy Regulations, 1973, stipulates that no oil shall be discharged into U.S. or foreign internal waters or prohibited zones. The U.S. prohibited area is designated as waters within 50 miles of the U.S. coastline.

APPENDIX B

Theory

A plane wave of light can be reflected, diffracted, and refracted from an object whose dimensions are of the same order as the wavelength of the light. The angular intensity distribution of the radiation scattered from a single particle can be rigorously described by Mie theory. The factors involved in determining the scattering behavior of an object include: the wavelength of the incident light, λ; the radius of the object, a; the index of refraction of the object, n; the index of refraction of the medium, n_m; the shape of the particle; and the number of particles in the scattering region. The calculation of scattering patterns with Mie theory involves an infinite series, and as particles become larger, more terms in the series must be calculated.

A standard computer code is available for calculating Mie scattering patterns (Dave, '68). Nevertheless, the process is time-consuming, and poorly suited for use in reducing data for real-time diagnostic purposes. A number of approximate theories have been developed for light scattering in well defined cases. For particles much smaller than the wavelength of light, (<.5 micron) Rayleigh scattering theory may be used. This involves a simple closed expression. For intermediate-sized particles (5-30 micron) anomalous diffraction theory can be used. The expression is (van de Hulst, '81):

$$I(\theta) = K^2 a^4 [A(a, n_o)]^2 I_O$$

<< Dave, J.V. "Subroutine for Computing the Parameters of the Electromagnetic Radiation Scattered by Spheres," IBM Order Number 360D-17.4.002 (1968).>>

where the scattering distribution A is a complex expression of Bessel functions. The advantage of using this expression is that empirical scattering data may be used to define the angular intensity distribution. For particles much larger (> 100 micron) than the wavelength of light, ray optics can be used to trace the path of the radiation through the particle. In a real flow system, a wide particle size distribution must be anticipated, and the approximate methods based on the assumption of a certain size particle are not valid.

An alternative to these approximate methods is Fraunhofer diffraction theory applied to the small angle scattering of light by a particle. The forward scattered light is primarily a result of diffraction from the edges of the particle. This can be pictured with Huygen's principle as secondary wavelets passing through a small orifice. According to Babinet's principle, an orifice and an opaque particle give the same diffraction pattern. The expression for Fraunhofer diffraction is:

$$I \propto I_0 \left[\frac{2J_1(y)}{y}\right]^2$$

where J_1 is the first order Bessel function and y is given by:

$$y = \frac{2\pi a}{\lambda} \sin\mu$$

A plot of intensity versus y_2 is given in Figure B-1. Fraunhofer diffraction is generally valid in the range when cos μ = 1.

<< van de Hulst, H.C. "Light Scattering by Small Particles," Dover, (1981).>>

Fraunhofer diffraction is the most widely used optical method of particle size determination. The expression is independent of refractive index, making it possible to determine particle size distributions for a wide range of materials. There are several methods commonly used to invert experimental scattering data to obtain particle size distributions.

Fraunhofer scattering is observed by passing a plane wave through a suspension of particles which scatter the radiation incoherently. The Fourier transform propery of a collecting lens is used to convert the angular distribution of the scattered light to a spatial distribution in the focal plane of the lens. The expression for the angular intensity distribution is given by:

$$I(\theta) = \frac{1}{\theta^2} \int_o^\infty a^2\, n(a)\, J_1^{\,2}(y)\, da$$

where n(a) is the particle size distribution function. In all cases, data is taken at intervals and light is scattered by a finite number of particles, so the integral may be written as a sum.

There is an analytical inversion of the integral expression for the angular intensity function. The Titshmarsh transform is given by:

$$n(a) = \int_o^\infty y\, J_1(y)\, Y_1(y)\, \frac{d}{}\, [\theta^3 I(\theta^3 I(\theta)]$$

where y_1 is the Bessel function of the second kind. Important features of the equation are that the integral is over a wider range ($\theta=0$ to $\theta=\infty$) than either the possible data or the range of validity of the Fraunhofer scattering approximation. In addition, the derivative of the data must be taken, after it is multiplied by a larger factor (θ^3).

Far simpler methods have been used to invert the scattering data. One method involves assuming a fixed form of the particle size distribution, and then fitting the variable parameters to the scattering data. This method has severe limitations such as variable sensitiviity to different oils, different flow conditions or changing temperature. A more applicable method involves the use of a matrix inversion. The scattered light is described by:

$$I(\theta) = \sum_{k=1}^{N} n(a)\, A_k(\theta)$$

where $A(\theta)$ is the scattering from an individual particle, and N is the total number of different sized particles to be considered. If j different angles are considered, this expression becomes:

$$I_j = A_{jk}\, n_k$$

and the inversion is simply

$$A^{-1}\, I = n$$

This method has been criticized, since A may be poorly suited for inversion. If the problem is over-determined (i.e., more data points for $I(\theta)$ than desired for $n(a)$, then conditioning of A is possible. Noise in the data has also been cited as a more significant problem for this method than for the analytical inversion.

If the particle size range, the wavelength of light and the detector geometry are balanced so that only the most intense part of the scattering pattern is used, then this method is actually less sensitive to noise than the analytical inversion. This is accomplished by working inside the first diffraction null shown in Figure B-1.

The particle size and concentration are used to set up the expression for anomalous diffraction. The angular scattering profile for each size range and refractive index is stored in the microcomputer. The concentration of each size is used to determine the scatterers. This expression can be written in matrix form:

$$I(\theta) = \sum_{k=1}^{N} C_k A_k (n_o)$$

where the sum is over different refractive indices. The concentration of each different contaminant can then be determined by the matrix inversion method:

$$A^{-1} I = C.$$

OILY WASTE PROCESSING SYSTEM

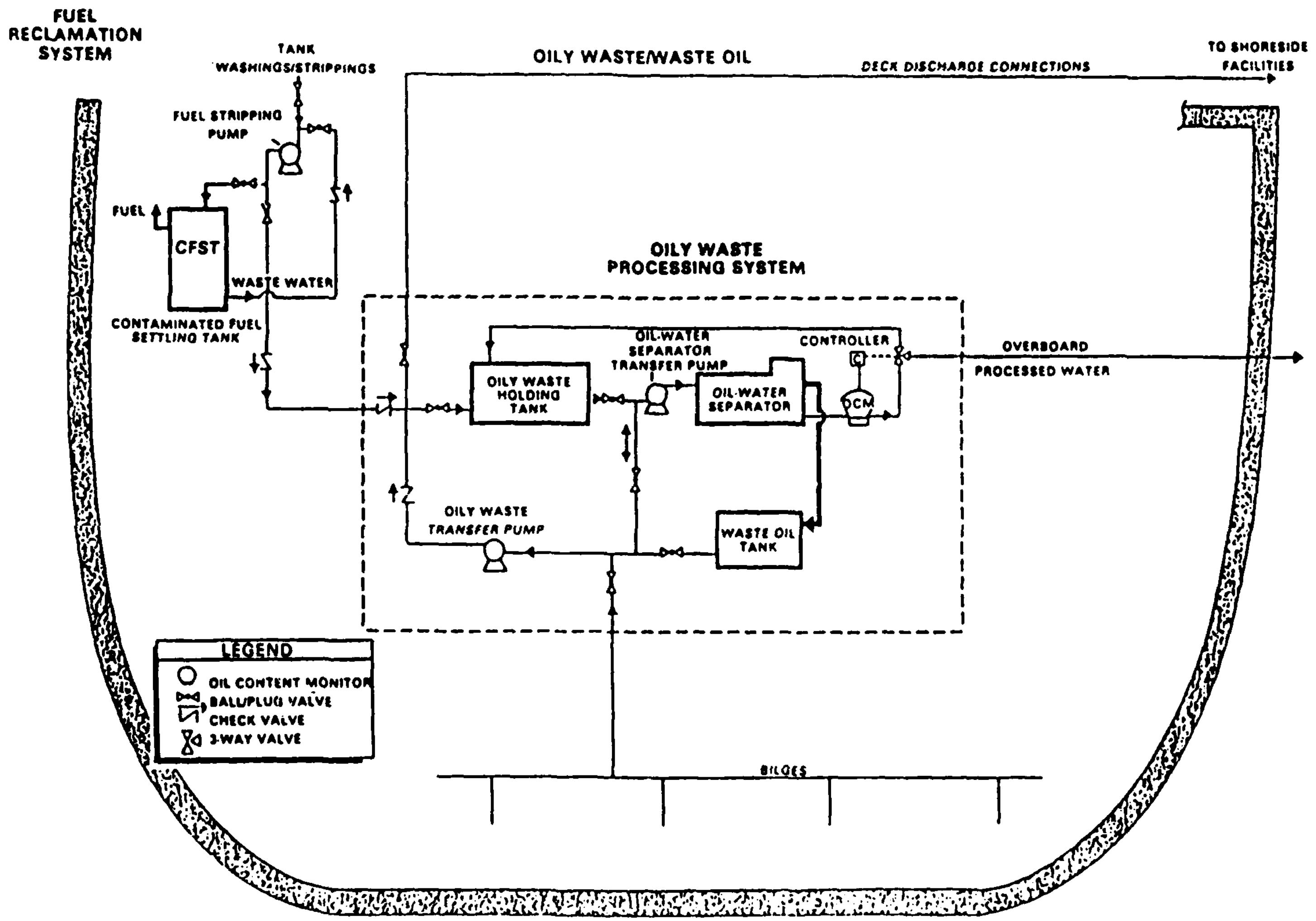

FIGURE 1

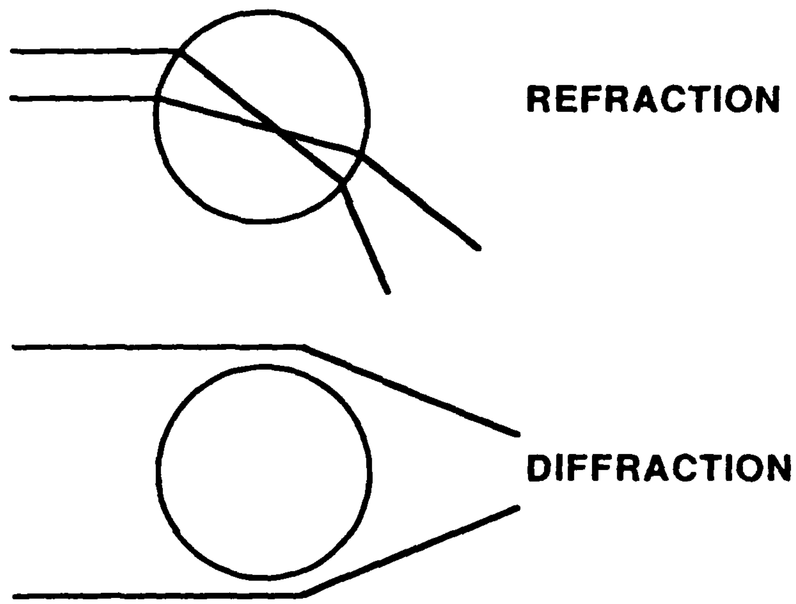

FIGURE 2. INTERACTION OF LIGHT WITH CONTAMINANT PARTICLES

FIBER OPTIC CONTAMINATION MONITOR
FORWARD SCATTERING SYSTEM

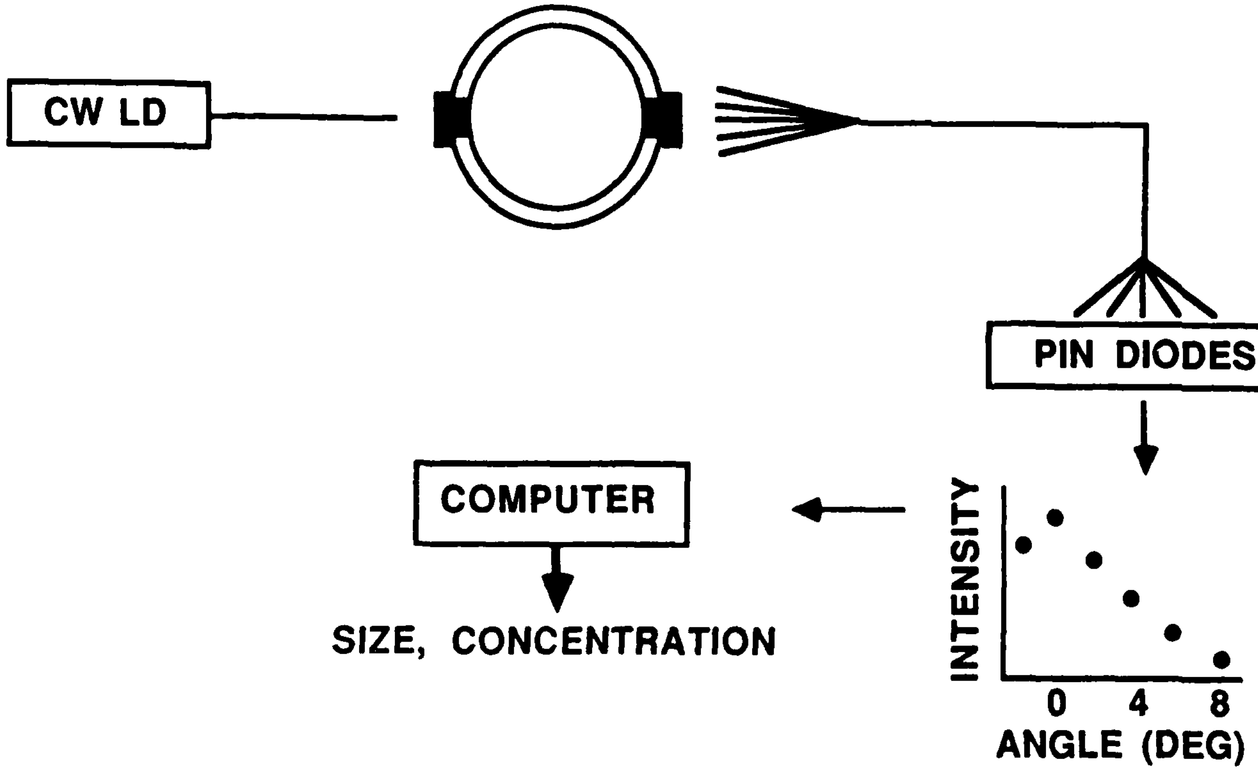

FIGURE 3

FIBER OPTIC CONTAMINATION MONITOR
LARGE ANGLE SCATTER SYSTEM

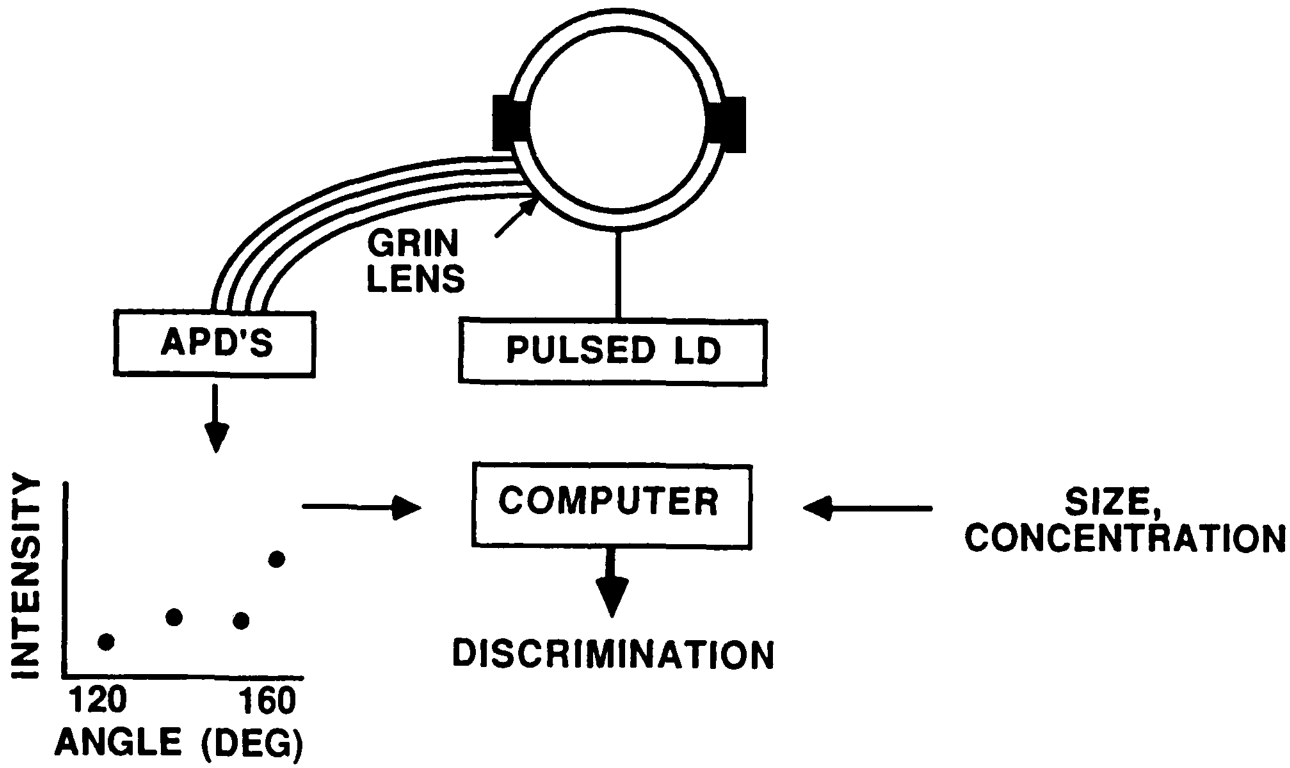

FIGURE 4

COMPARISON OF CHEMICAL ANALYSIS AND OIL MONITOR DETERMINATION OF CONCENTRATION

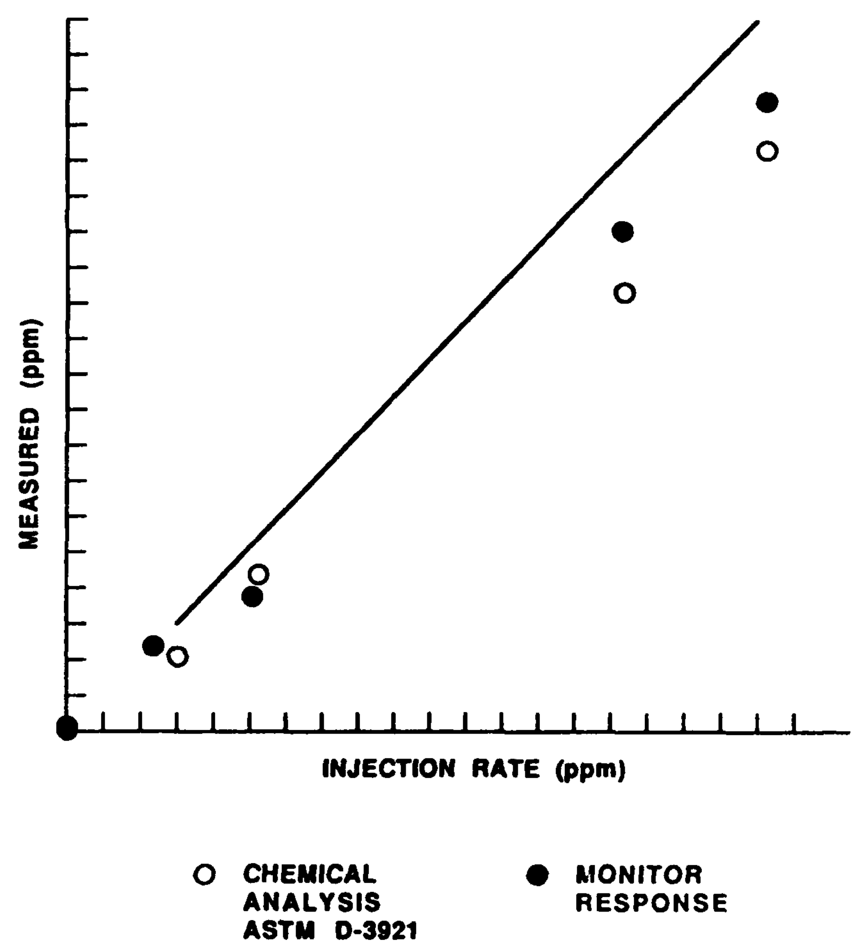

FIGURE 5

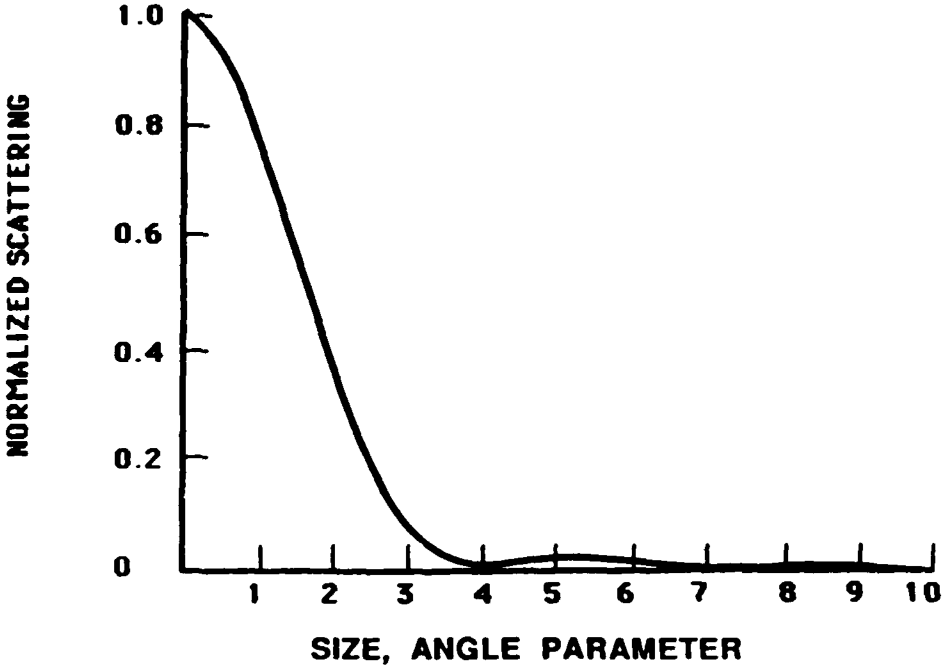

FIGURE B-1. PREDICTED SCATTER PATTERN BASED ON THE DIFFRACTION APPROXIMATION